GHz-THz Electronics

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Integrity ★ Service ★ Excellence

Report Documentation Page

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2013 AFOSR SPRING REVIEW
3001B PORTFOLIO OVERVIEW

NAME: Jim Hwang

BRIEF DESCRIPTION OF PORTFOLIO: GHz-THz Electronics

LIST SUB-AREAS IN PORTFOLIO:

I. **THz Electronics** – Material and device breakthroughs for transistors based on conventional semiconductors (e.g., group IV elements or group III-V compounds with covalent bonds) to operate at THz frequencies with adequate power. Challenges exist mainly in perfecting crystalline structure and interfaces as channel thickness is scaled to single atomic layer.

II. **Novel GHz Electronics** – Material and device breakthroughs for transistors based on novel semiconductors (e.g., transition-metal oxides with ionic bonds) to operate at GHz frequencies with high power. Challenges exist mainly in controlling purity and stoichiometry, as well as in understanding metal-insulator transition.

III. **Reconfigurable Electronics** – Material and device breakthroughs for meta-materials, artificial dielectrics, ferrites, multi-ferroics, nano-magnetics, and micro/nano electromechanical systems to perform multiple electronic, magnetic and optical functions. Challenges exist mainly in understanding the interaction between electromagnetic waves, electrons, plasmons and phonons on nanometer scale.

I. THz Electronics

- Sub-millimeter-wave radar & imaging
- Space situation awareness
- Chemical/biological/nuclear sensing
- Ultra-wideband communications
- Ultra-high-speed on-board and front-end data processing

Covalent Semiconductors

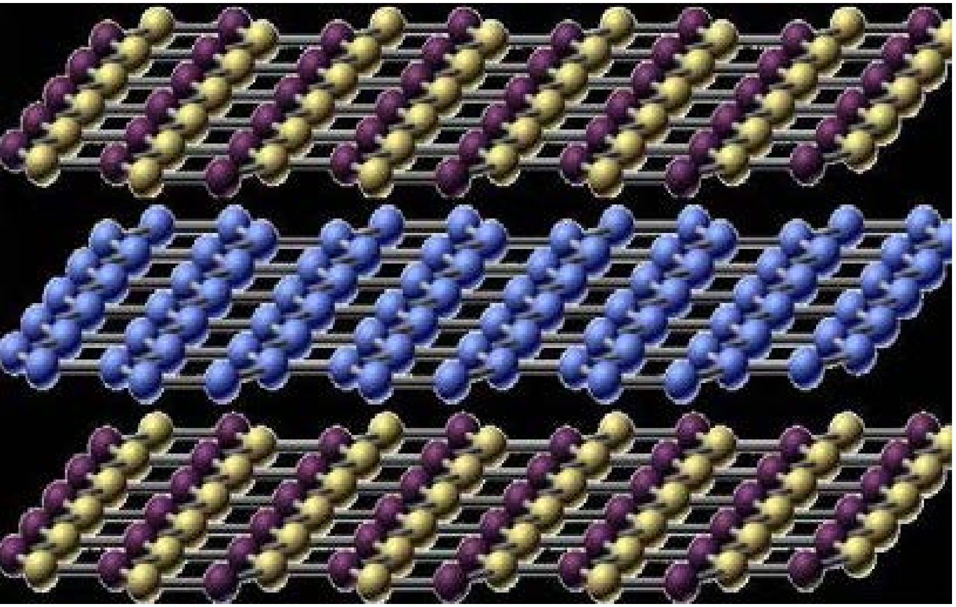
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo

- **Transition out GaN (MURI, STTR, AFRL, DARPA)**
- **Explore 2D materials and devices beyond graphene (FY14 BRI)**

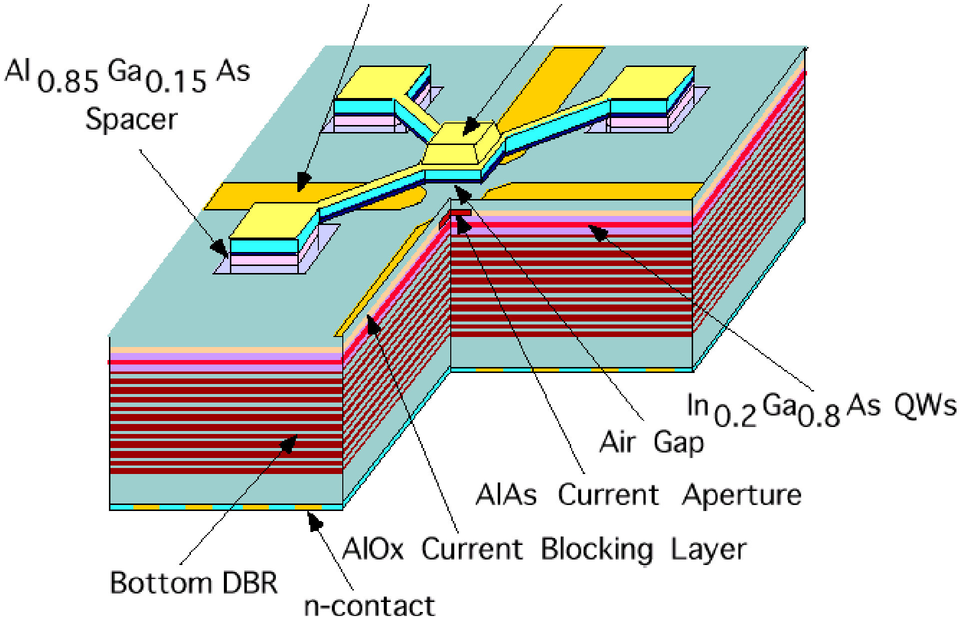
Jim Hwang, Gernot Pomrenke, Joycelyn Harrison & Misoon Mah (AFOSR)

- Graphene beautiful but difficult to deal with
- Best to mate graphene with other 2D layers through van der Waals force
- Graphene – conductor, 2D BN – insulator, 2D MoS_2 – semiconductor, 2D $NbSe_2$ – superconductor
- Bandgap of MoS_2 transitions from being indirect in bulk to direct in 2D
- Free of epitaxial strains, 2D heterostructures can do more wonders than 3D heterostructures

h-BN/Graphene/h-BN

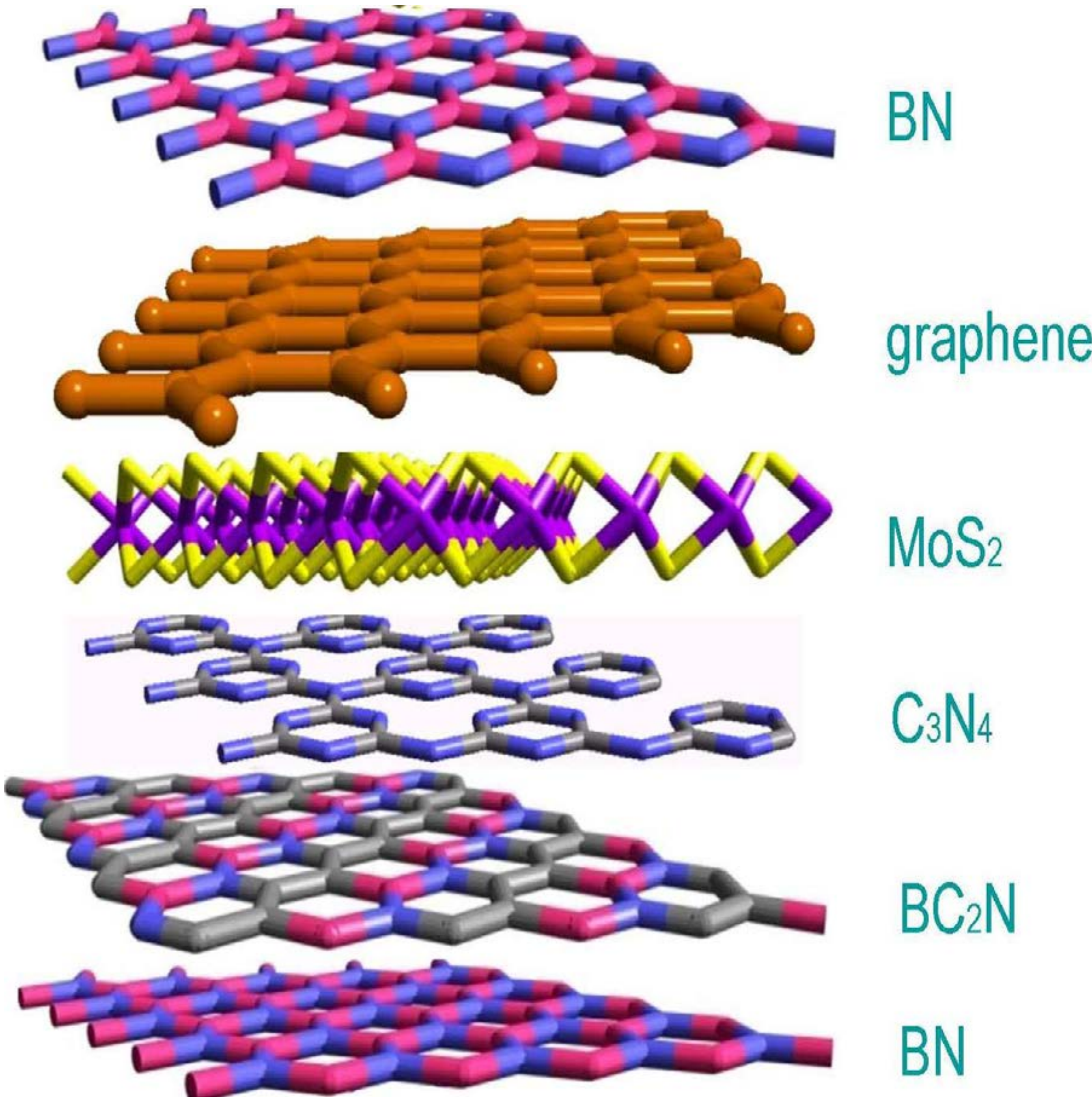


3D VCSEL Heterostructure



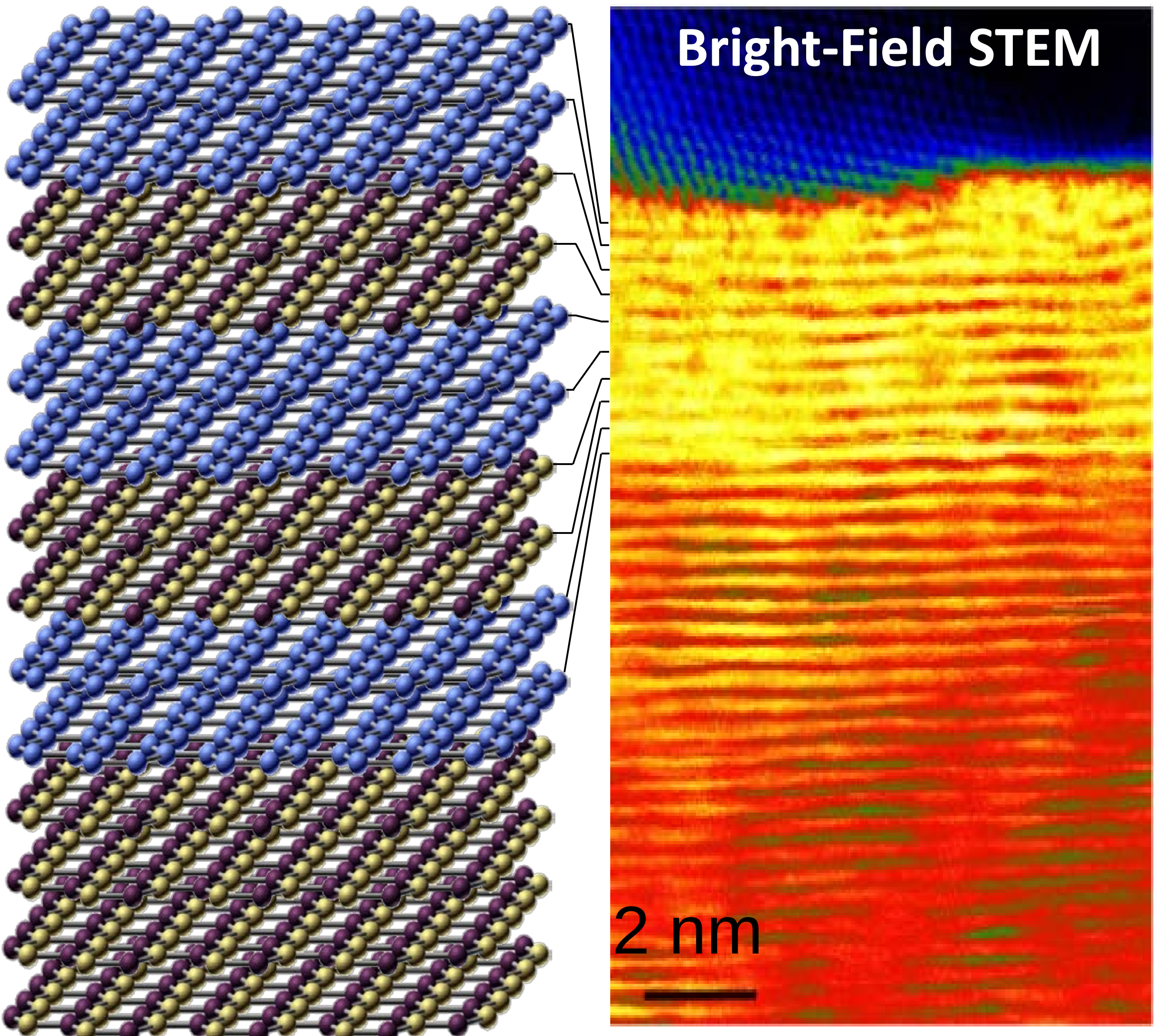
Challenges for 2D Heterostructures

- While new 2D layers continue to be synthesized, 2D heterostructure is in infancy
- Only graphene grown on BN substrate have comparable properties to that of exfoliated graphene
- Limited success for growing 2D BN on graphene without metal catalyst
- Little theoretical understanding/prediction of properties of 2D heterostructures



Graphene-BN Superlattice

Andre Geim & Konstantin Novoselov (Manchester, UK)

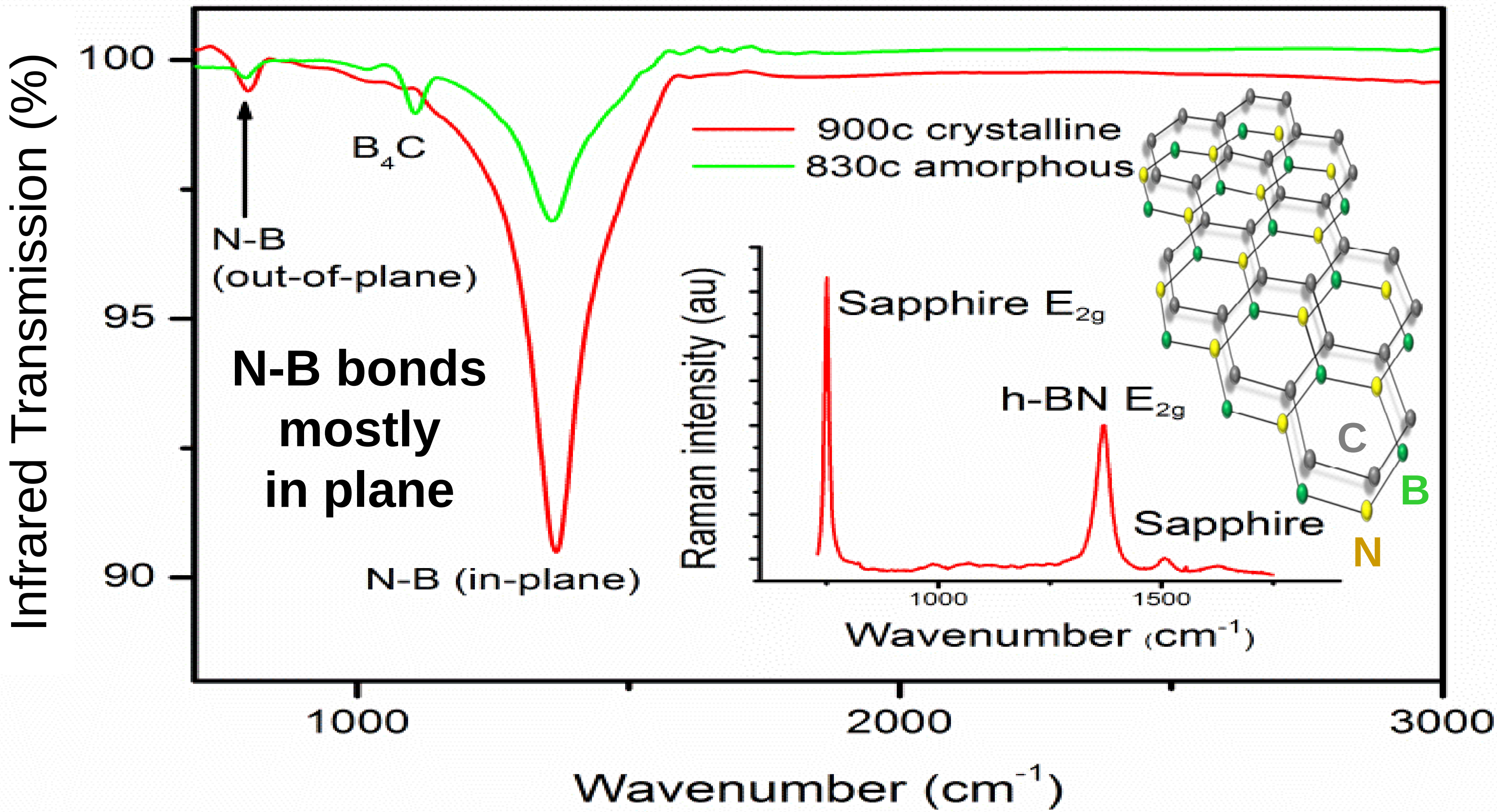


Remarkable achievement by exfoliation

cmilli.com

Atomic Layer Deposition of Hexagonal BN on Sapphire

Mike Snure & Qing Paduano (AFRL/RYDH)



Compared to state of the art by metal-organic chemical vapor deposition, atomic layer deposition promises monolayer control without metal catalyst

Molecular Beam Epitaxy of α-Sn on InSb

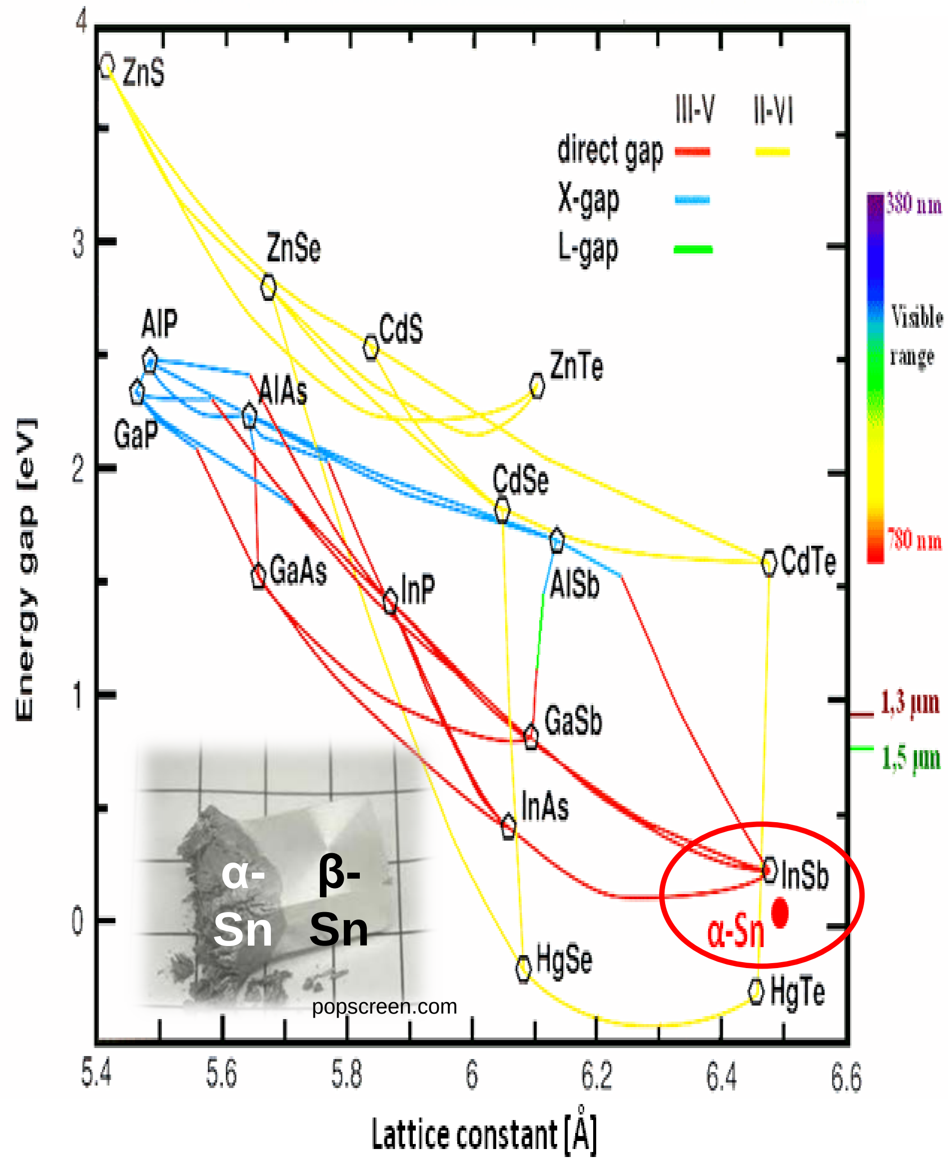
Arnold Kiefer & Bruce Claflin, AFRL/RYDH

Unique Properties of α-Sn

- Bulk α-Sn (cubic, zero-gap semi-conductor) transforms into β-Sn (tetragonal, metal) above 13 °C
- Epitaxial α-Sn on InSb stable to 130 °C
- Bandgap opens with strain
- Predicted to be a topological insulator
- 2D electron gas formed between α-Sn and InSb
- Little studied since 1981

Potential Applications

- Low-power, high-speed transistors
- Long-wavelength IR/THz detectors
- Phase-change memory material
- Non-polar active medium in III-V quantum-well heterostructures



II. Novel GHz Electronics

- Less demanding on crystalline perfectness
- Deposition on almost any substrate at low temp.
- Radiation hard, fault tolerant, & self healing
- High electron concentration w/ correlated transport
- Wide bandgap for high power and transparency
- Topological effects
- SWAP-C and conforming
- Metal-insulator transition with high on-off ratio

1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al		15 P	16 S	17 Cl	18 Ar
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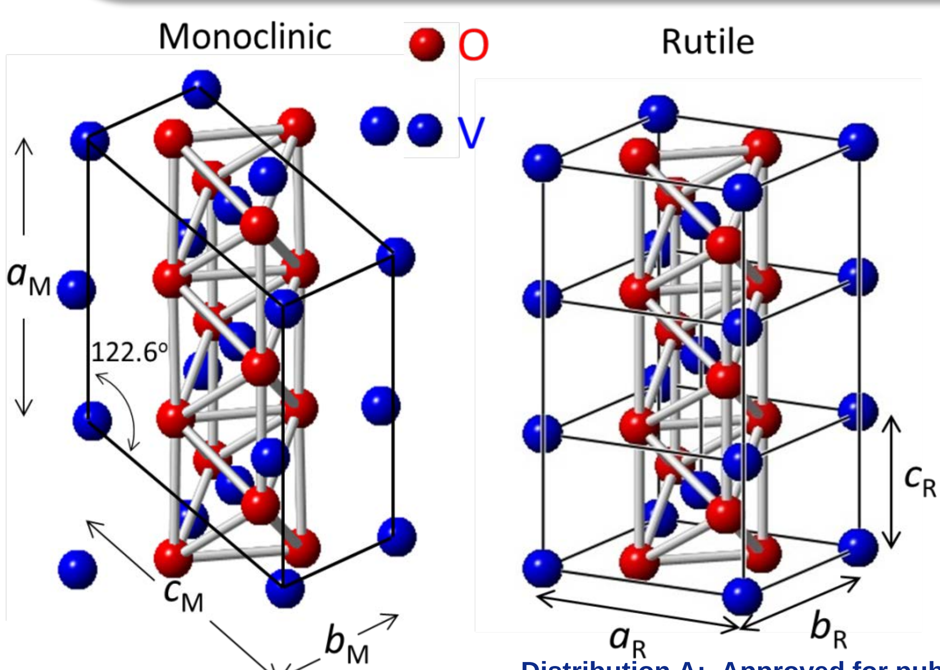
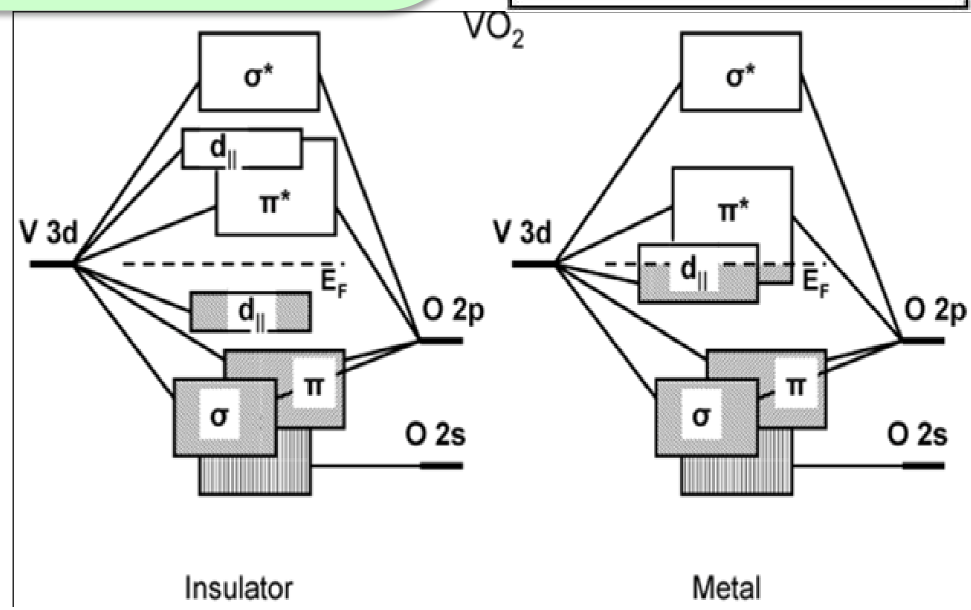
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Fl	115 Uup	116 Lv	117 Uus	118 Uuo
*Lanthanoids			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
**Actinoids			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

Transition Metal Oxides, Chalcog-enides

Metal-Insulator Transition

- Observed in some bulk oxide crystals in late 1950s
- On/off conductivity ratio can be much higher than that of semiconductors (10^8 vs. 10^6)
- Requires little energy for switching at threshold
- Transition can be triggered by temperature, pressure, light, electric field, etc. and as fast as 100 fs
- What changes first? Structural or electronic?



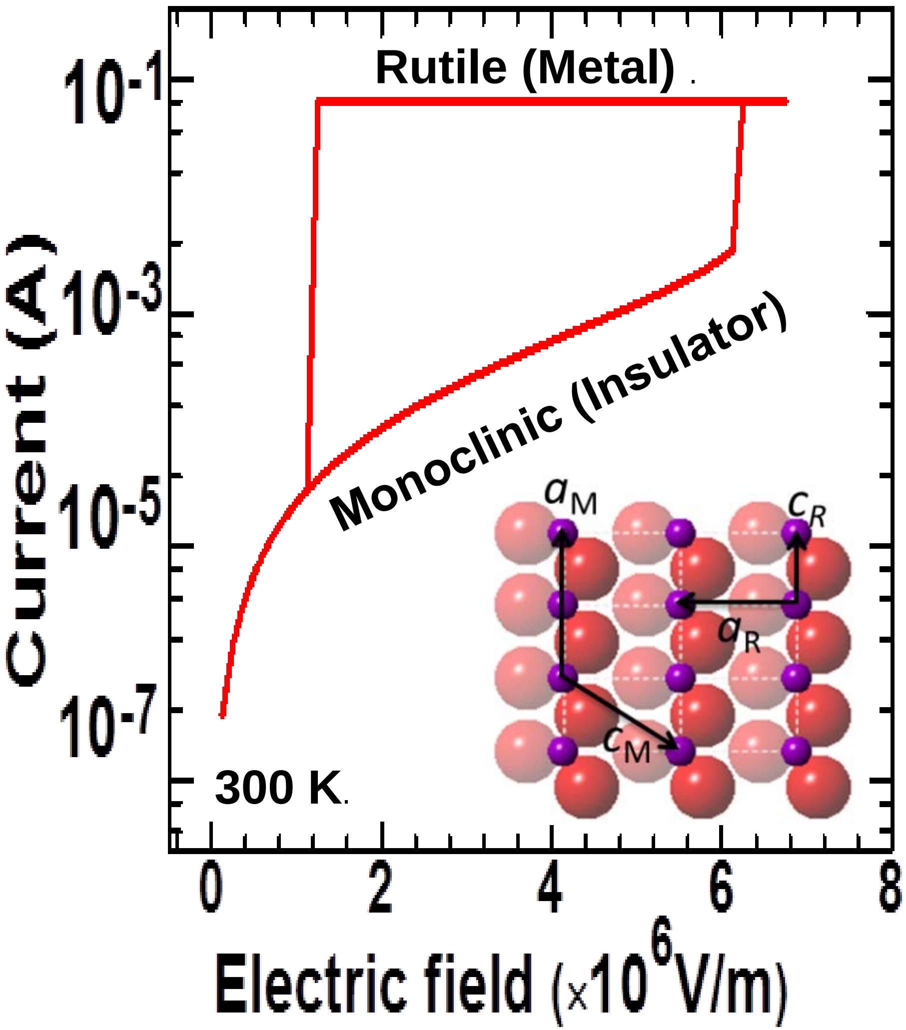


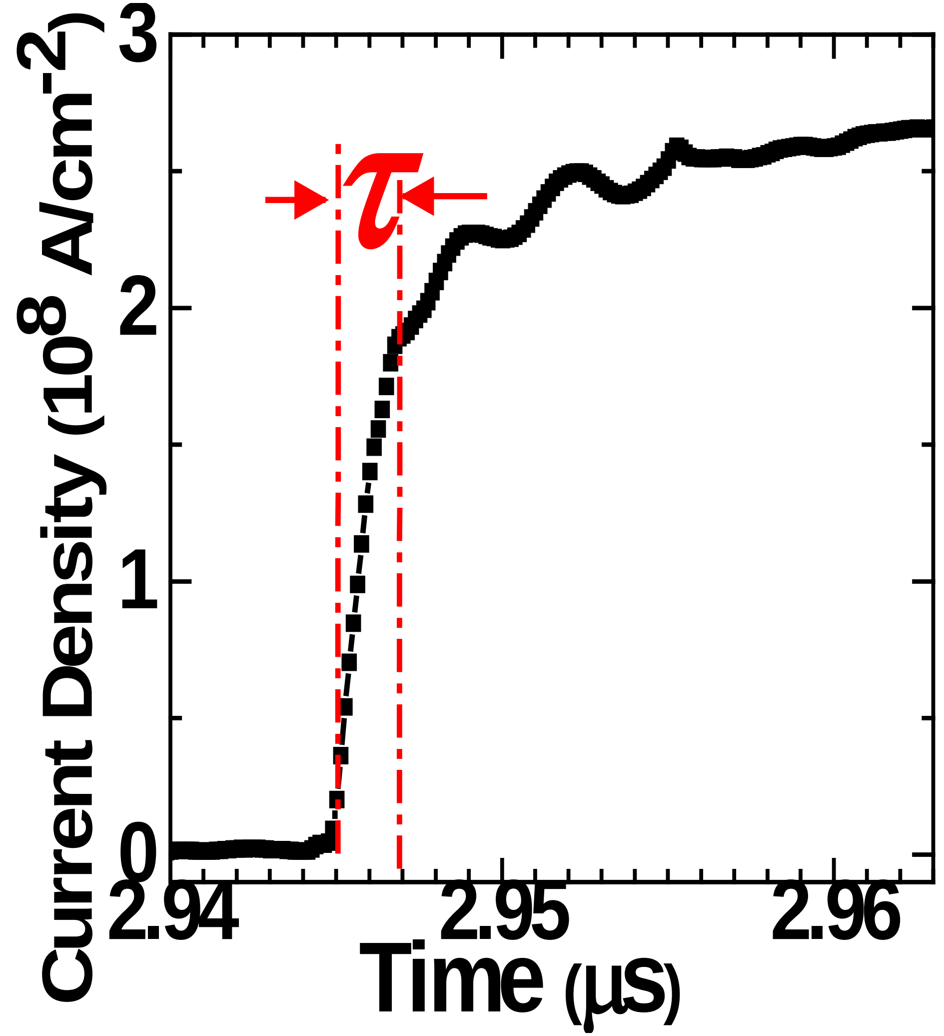
J. B. Goodenough, JSSC, 1971

Nanosecond Metal-Insulator Transition in VO_2

Shriram Ramanathan (Harvard)

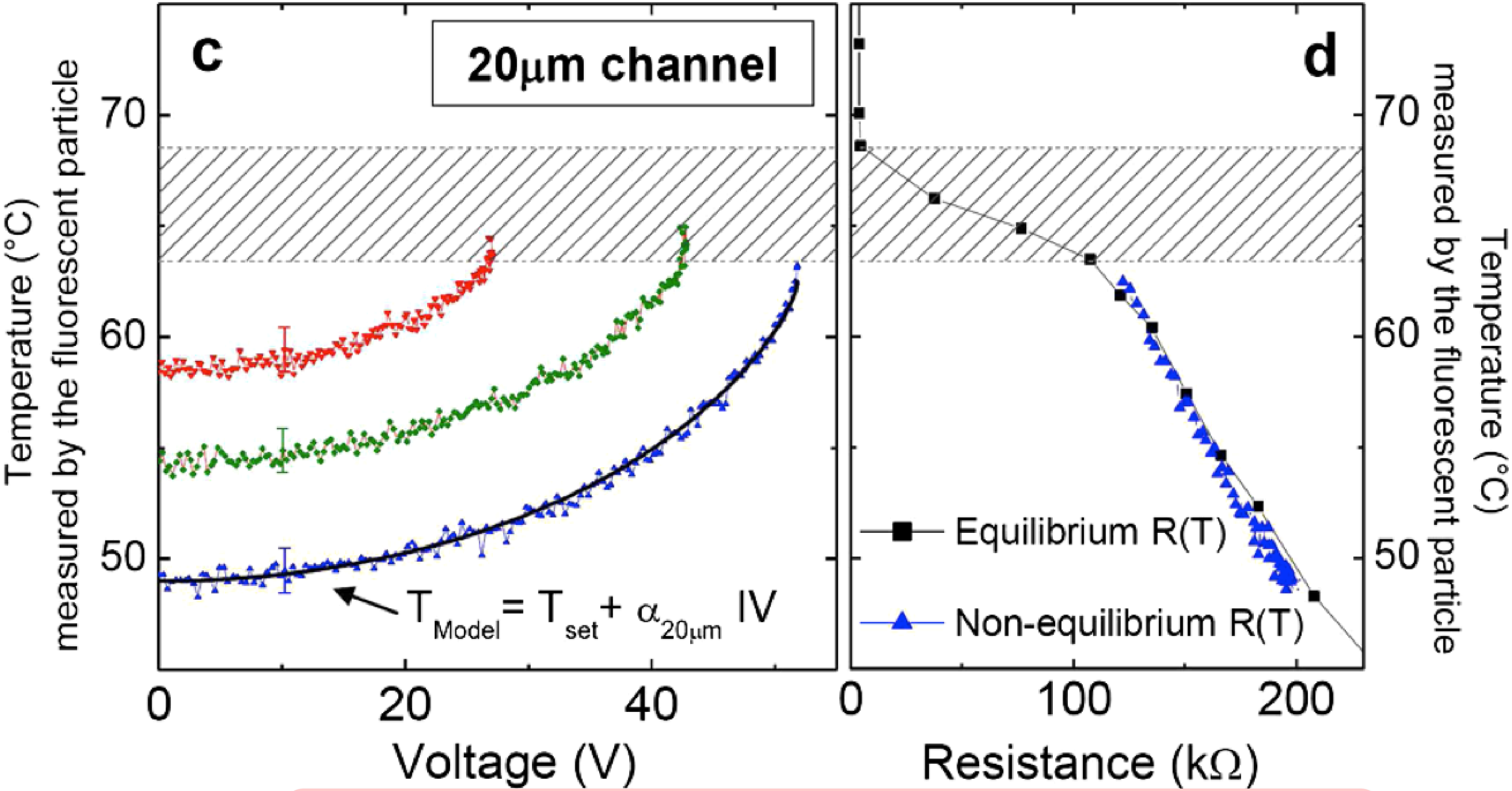
Polycrystalline VO_2 on Au by RF-sputtering with precise control of O_2 pressure





Micro-Thermometry of Metal-Insulator Transition in VO_2

Ivan Schuller (UCSD)



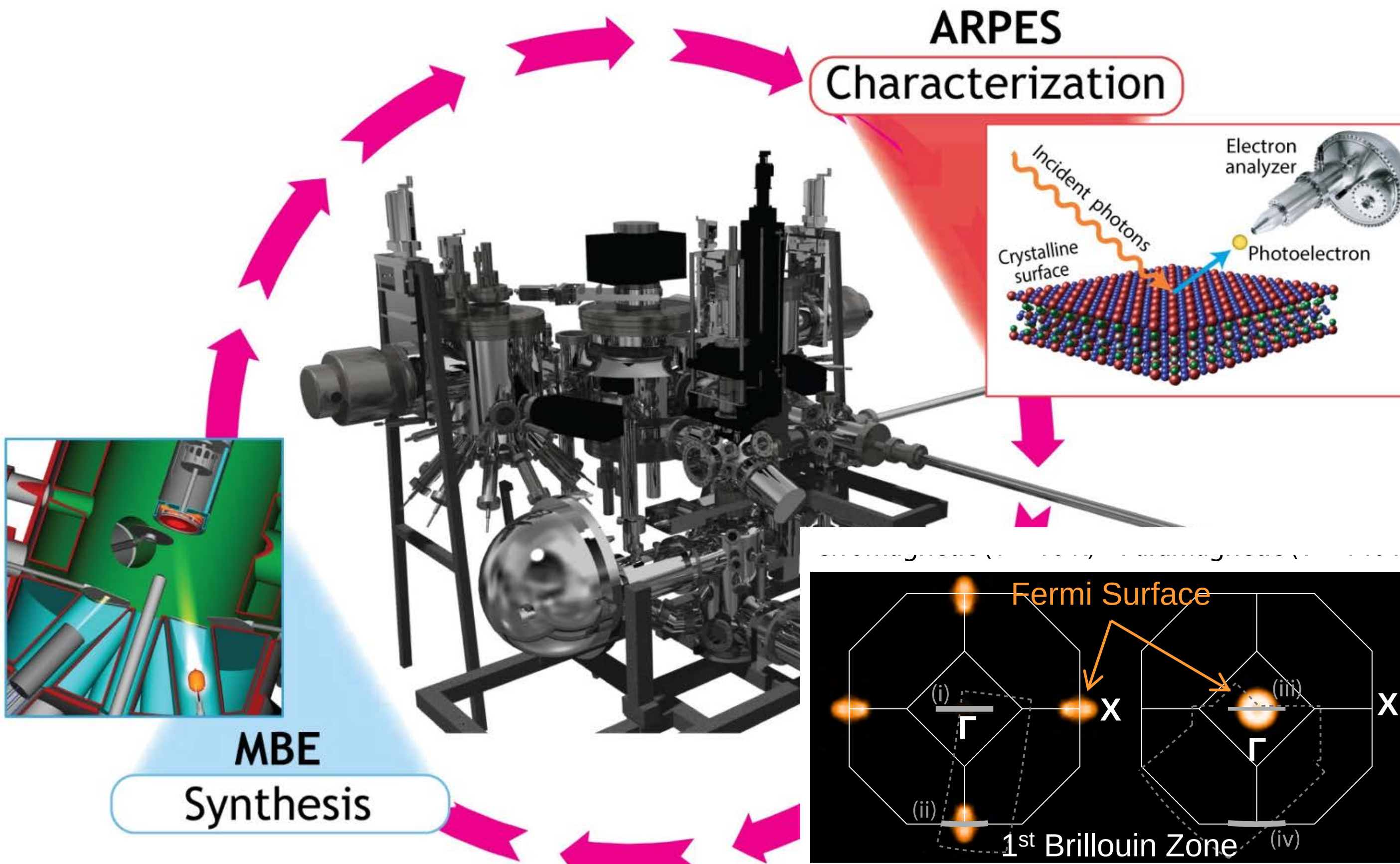
Voltage- or current-induced transition appears to be due to Joule heating

Metal-Insulator Transition in EuO

Darrell Schlom & Kyle Shen (Cornell)

Tight coupling of molecular-beam epitaxy (MBE) and angle-resolved photoelectron spectroscopy (ARPES) reveals metal-insulator transition involving massive Fermi surface reconstruction.

- **Lack of carrier activation arises from defect states near Γ point.**
- **Reduce defects (including dopant clustering) to enable controlled doping.**
- **Combine strain and doping to boost Curie temperature.**



Collaboration

- Gernot Pomrenke – 2D materials & devices
- Harold Weinstock – nanoscale oxides
- Joycelyn Harrison – 2D materials
- Ali Sayir - oxides

- Dan Green – oxide electronics
- Paul Maki – nitride electronics
- Chagaan Baatar – 2D materials

- Marc Ulrich – topological insulators
- Pani Varanasi – 2D materials
- Mike Gerhold – transistor lasers

- Dev Palmer – THz & nitride electronics
- Jeff Rogers – topological insulators
- Brian Holloway – 2D materials

- Tony Esposito & Kiki Ikossi
  – THz applications

- Anu Kaul & Charles Ying
  – 2D materials & devices
- Dimitris Pavlidis
  – THz electronics

- Kwok Ng
  – beyond Si

Take-Away Messages

FY12 FY13 FY14

I. THz Electronics –
Explore 2D materials and devices

FY12 FY13 FY14

II.Novel GHz Electronics –
Understand metal-insulator transition

FY12 FY13 FY14

III.Reconfigurable Electronics –
Formulate strategy this year